HYPERSONIC FLOWS AS RELATED TO THE NATIONAL AEROSPACE PLANE

Semi-Annual Research Report

for

Cooperative Agreement No.: NCC2-452

for the period

September 1, 1991 - May 31, 1992

Submitted to

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035

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30 July, 1992

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I. EXPERIMENTAL WORK

The results of the May, 1991, tunnel entry (double fin - intersecting shocks) have been published as NASA TM 103909. These results have also been submitted to the January, 1993, AIAA meeting in Reno, NV. The paper presented at the Summer, 1991, AIAA meeting (AIAA 91-1761) has been accepted in the AIAA Journal.

In addition, a new basic geometry (double fin with upper compression surface) has been designed and fabricated. This geometry will more closely simulate the NASP hypersonic inlet. This test model will be experimentally investigated during a tunnel entry scheduled for Spring/Summer, 1993.

APPENDIXES

1. M.I. Kussoy and K.C. Horstman, *Intersecting Shock-Wave/Turbulent Boundary-Layer Interactions at Mach 8.3*, NASA TM 103909, 2/92.

2. M.I. Kussoy and K.C. Horstman, *An Experimental Study of a Three-Dimensional Shock/Wave Turbulent Boundary-Layer Interaction at a Hypersonic Mach Number,* submitted for publication.

3. M.I. Kussoy, K.C. Horstman, and C.C. Horstman, *Hypersonic Crossing Shock-Wave / Turbulent Boundary-Layer Interactions*, submitted for the AIAA 31st Aerospace Meeting, Reno, NV, January 1993.

II. THEORETICAL WORK

1. BACKGROUND

The study in the last 6 months has observed a clear evidence that the current two-equation models tend to under-predict flow separation and over-predict heat transfer rate near flow re-attachment regions. In hypersonic flow calculations, these model deficiencies appear to be even more pronounced. This is particularly true in the incapability of the model to predict the extent of the flow separation.

In the investigation of several popular models in predicting hypersonic flow two modifications to the current models have been proposed to remedy the above mentioned difficulties. The first one, designed to reduce the heat transfer rate near flow-reattachment, involves the limiting of the turbulence length scale by the von Karman length scale. Under the framework of the $k - \epsilon$ model, the standard, or unmodified turbulent viscosity can be expressed as:

$$\mu_t = c_\mu \rho k^{1/2} l f$$

where $l = k^{3/2}/\epsilon$ is the turbulent length scale and f is the damping function. The modification to the turbulent length scale is given by

$$l = \min(\kappa c_\mu^{-3/4} y, k^{3/2}/\epsilon)$$

The other, designed to increase to size of separation bubble, allows the length scale to reduce (or increase) subject to rapid flow compression (or expansion). The basic principle of this development is based on the fact that the product ρl^n remains constant subject to a deformatin, where $n = 1,2,3$ correspond to linear, cylindrical and spherical deformations, respectively. By applying the continuity, the equation yields,

$$\frac{1}{l}\frac{dl}{dt} = \frac{1}{n} u_{k,k}$$

In contrast, by applying rapid distortion to the flow field, the k and ϵ equation can be written as;

$$\frac{dk}{dt} = -\frac{2}{3} u_{k,k} k$$

and

$$\frac{d\epsilon}{dt} = -\frac{2}{3} c_{\epsilon,3} u_{k,k} \epsilon$$

By manipulating of k and ϵ equations, the length scale equation yields;

$$\frac{1}{l}\frac{dl}{dt} = (\frac{2}{3} c_{\epsilon,3} - 1) u_{k,k}$$

By comparing the above two length equations, it can be shown that $c_{\epsilon,3}$ should take a value of $3/2(1 + 1/n)$ instead of $c_{\epsilon,1}$.

2. RESULTS COMPARED TODATE

The experimental data used in the current comparisons are selected based on the recommendation of Settles and Dodson [1991], in which a large selections of experiments were reviewed. Three experimental data sets chosen for comparison are (1) Hypersonic Flare flows of Kussoy and Horstman, (2) 2-D Hypersonic compression corner flow of Coleman and Stollery and (3) Ogive-cylinder flows interacting with a shock-generator ring of Kussoy and Horstman.

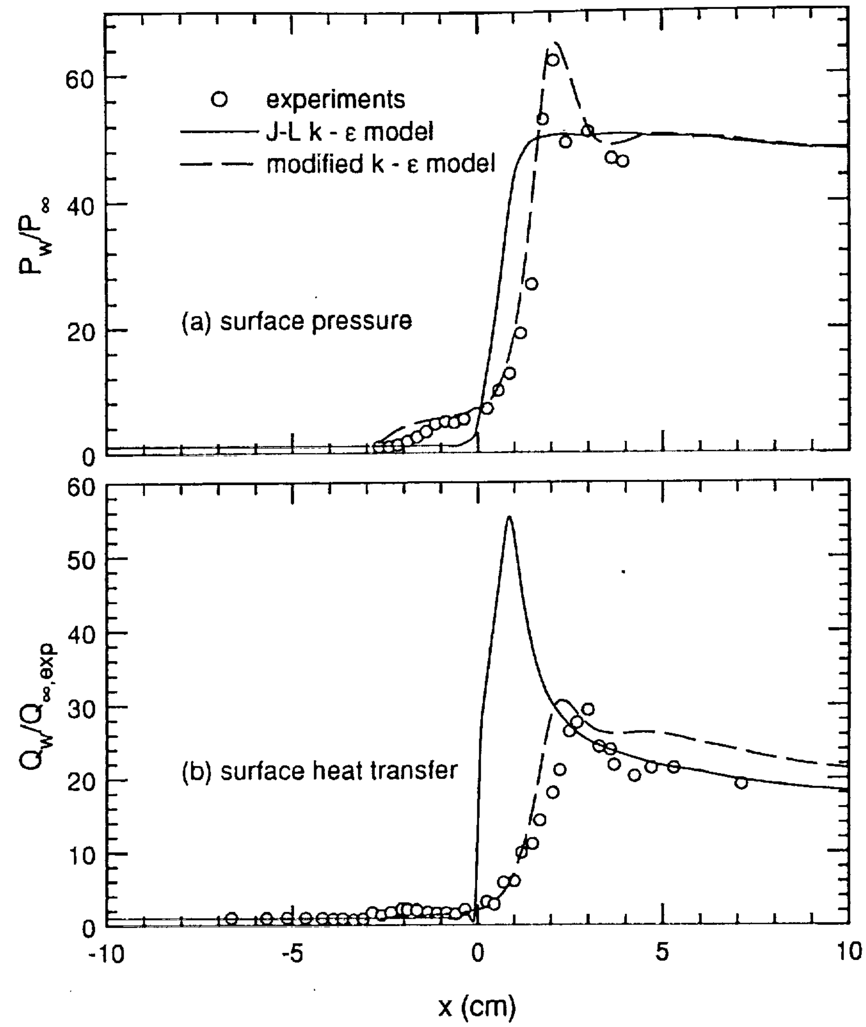

Figure 2. Prediction of surface pressure and heat transfer of a hypersonic flow over a 2-D compression 34^o corner

2.2 M = 9.22, 2-D Compression Corner

The next case to be discussed consists of shock-wave and boundary-layer interactions induced by a 2-D compression 34^o corner in a hypersonic flow at a free-stream Mach number of 9.22 [Coleman and Stollery, 1972]. The free-stream and surface temperatures are 64.5K and 295K, respectively. The numerical simulation were made with a 141 by 140 mesh and with 60-80 grids inside the boundary layer. Figures 2(a) and 2(b) shows surface pressure and heat transfer predictions, respectively, obtained by both the Jones-Launder $k - \epsilon$ model and its modified version. The failures of the Jones-Launder model in predicting flow separation and surface heat transfer is clearly depicted in the figures. On the other hand, the modified version results in a better agreement in predicting flow separation and as a consequence is able to capture the pressure peak near flow re-attachment. Furthermore, the over-prediction of the heat transfer rate near the flow re-attachment is reduced to the expected level.

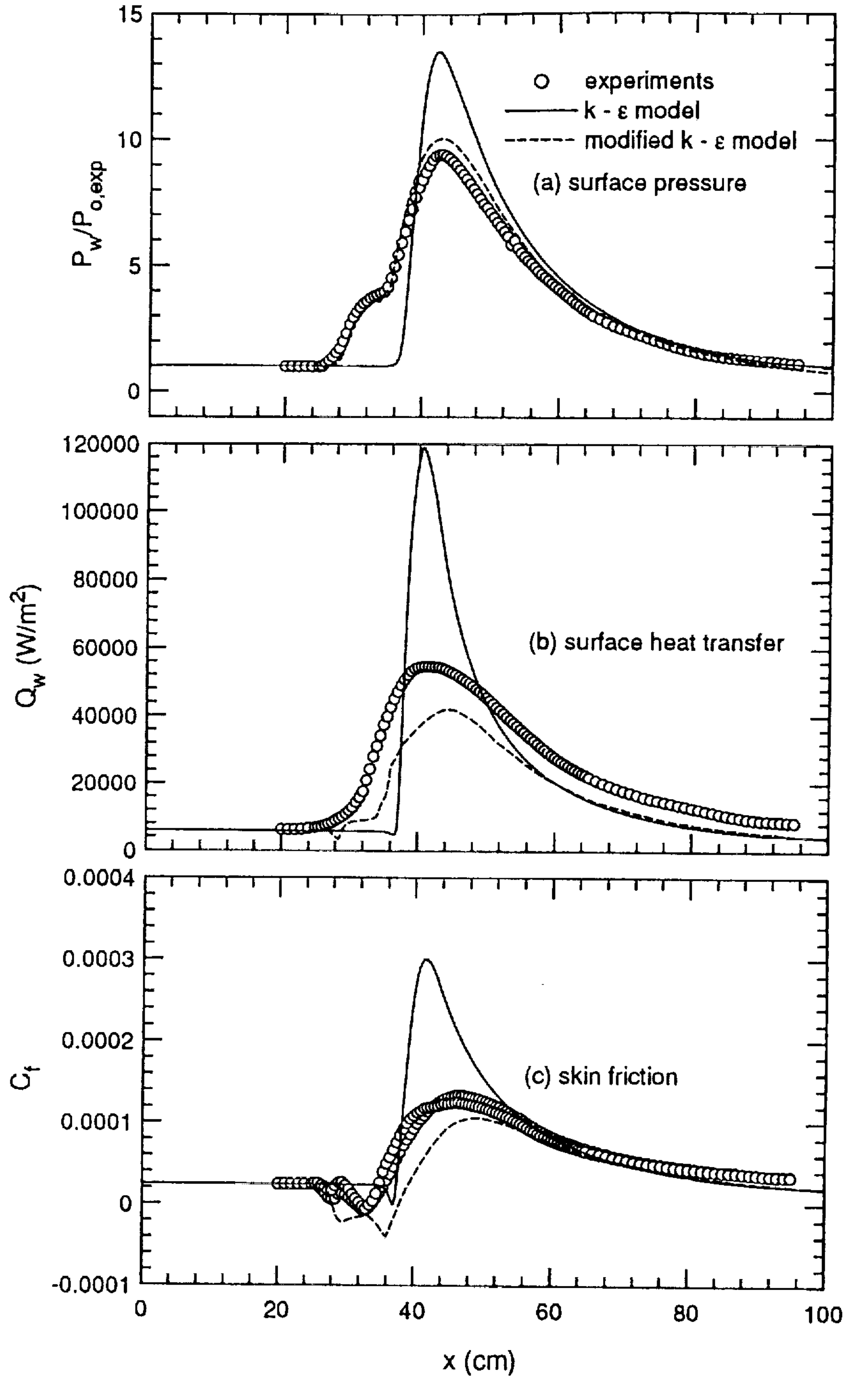

Figure 3. Prediction of surface pressure, heat transfer and skin friction of an axisymmetric impinging shock

2.3 M = 6.86, Axisymmetric Impinging Shock

This case consists of a 15^o shock-generator wedge used to induce shock-wave boundary layer interactions on an ogive cylinder [Kussoy and Horstman, 1975]. The free-stream Mach number at the tip of the shock-generation wedge is 6.86 and the temperature is 67.8K. The cylinder wall temperature is fixed at 300K. The computation is made with a 141 by 200 mesh and with grids being compressed both near the cylinder wall and the shock-generator wedge.

Figures 3(a), 3(b) and 3(c) show the comparisons of the predicted surface pressure, heat transfer and skin friction, respectively, obtained by the Jones-Launder $k-\epsilon$ model and the modified version. As can be seen from the figures, the Jones-Launder $k-\epsilon$ model fails to predict the flow separation and over-predicts the heat transfer and the skin friction near flow reattachment. Once again, the modified version correctly predicts the size of flow separation and gives rise to better results for the heat transfer rate and skin friction.

3. CONCLUSION

Two major deficiencies of the current two-equation models in predicting complex hypersonic flows have been reported, i.e. under-prediction of flow separation and over-prediction of peak heat transfer rate. Two modifications to the $k-\epsilon$ model were reported and tested over a range of flows. Based on our limited study, the modified models have been found to give better agreements in both surface pressure and heat transfer predictions for several complex shock-wave boundary-layer interaction flows. However, in order to confirm our observation, more calculations will be performed in the future study covering a wider range of flows and conditions than reported here.

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